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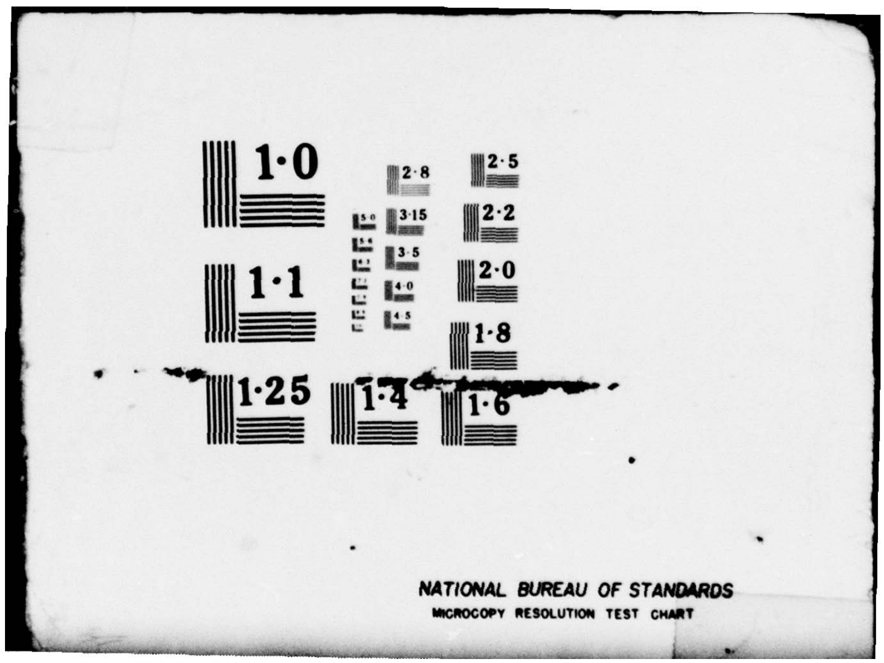
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INTERIM SCIENTIFIC REPORT

Submitted to:

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Bolling Air Force Base, D.C. 20332
(Attn: Major Charles L. Nefzger)

CONTROL STRATEGIES FOR COMPLEX SYSTEMS FOR USE IN AEROSPACE AVIONICS

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This interim scientific report highlights the results obtained during the period 1 July 1978 to 30 June 1979, on a research project devoted to the development of concepts and methodology for the analysis and synthesis of control strategies for complex systems. The results are documented in journal articles, meeting papers, and technical reports cited in the list of publications. The results are summarized under the following headings: Sensitivity adaptive feedback with estimation redistribution, sensitivity reducing compensators using observers, design of optimal systems with low sensitivity to small time (cont) next page

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20. Abstract (cont)

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ABSTRACT

This interim scientific report highlights the results obtained during the period 1 July 1978 to 30 June 1979, on a research project devoted to the development of concepts and methodology for the analysis and synthesis of control strategies for complex systems. The results are documented in journal articles, meeting papers, and technical reports cited in the list of publications. The results are summarized under the following headings: sensitivity adaptive feedback with estimation redistribution, sensitivity reducing compensators using observers, design of optimal systems with low sensitivity to small time delays, output feedback compensator design, zeros of multivariable systems, optimal control of a class of singularly perturbed nonlinear systems, Newton-Lyapunov design for a class of nonlinear regulator problems, variable structure model following control systems, and robust control system design.

I. Faculty Employed on Grant During the Year

Jose B. Cruz, Jr., Professor, Principal Investigator
William R. Perkins, Professor
Petar V. Kokotovic, Professor
Juergen Ackermann, Visiting Professor

II. Summary of Research Accomplishments

A. Sensitivity Adaptive Feedback with Estimation Redistribution

We have developed recently an approach to the synthesis of dynamic controllers for systems containing unknown random parameters. This approach, called SAFER control, allocates individual parameter estimation costs for a given total parameter estimation cost, so as to minimize the primary control cost function. This is achieved by appropriate choice of controller gains from the dynamic controller and choice of weighting coefficients for the sensitivity functions which are related to the parameter estimation accuracy. Some simplification can be effected when output sensitivities rather than state sensitivities are used. The general output SAFER problem is still quite complicated and the algorithm is still numerically complicated. Under investigation is a class of single-input single output discrete-time system with unknown random parameters. This is the class treated by the theory of self-tuning regulators of Astrom and his group over the past 15 years. Using only a one-step ahead minimum mean square error criterion, as in the self-tuning regulator case, the SAFER algorithm is drastically simplified. Furthermore, the sensitivity adaptation is also over a single stage in the future. The general conceptual framework for SAFER control is described in [B4].

The SAFER concept was applied to a model for a magnetic suspension system to obtain some numerical and simulation experience with the method [C2]. It appears that the origianl SAFER algorithm is relatively too time consuming but perhaps the simplification to the one-step ahead minimization for single-input single output systems might be practical but this has not been tried as yet. The associated on-line estimation via an extended Kalman filter was numerical unsatisfactory but a mathematically equivalent and numerically superior method using matrix factorization indeed improved the numerical stability problem [C2].

B. Sensitivity Reducing Compensators Using Observers

We developed the concept of comparison sensitivity for multivariable systems several years ago as a tool for assessing the benefits of feedback. Linear optimal state regulators were found by Kreindler to automatically satisfy our sensitivity criterion. Recently Naeije and Bosgra extended Kreindler's result to output feedback controls using dynamic compensators. Implementing a full state feedback law using an observer to estimate the unmeasured states will not satisfy the output sensitivity reduction criterion in general. We have developed an extension of Naeije and Bosgra to the particular case of output feedback system using state observers [A2,A4]. An interactive software has been developed and applied to a simple aircraft control example [A2]. The design procedure using observers is an improvement over the design with arbitrary compensator dynamics for the following reasons. First, the design of the observer is well-known and by placing the poles of the observer the designer is selecting poles of the overall feedback system. Second, the dynamic order of the reduced order observer is less than the maximum bound on the dynamic order of the compensator designed by the methods of Naeije and Bosgra. Finally, the use of observers leads to a useful interpretation of the sensitivity weighting matrix [A2].

C. Design of Optimal Systems with Low Sensitivity to Small Time Delays

The project is concerned with a study of trajectory sensitivity of optimal control systems. The parameter with respect to which sensitivity is studied is a small undesirable time delay that might occur in a system design nominally with zero delays. Small time delays are usually expected to occur in systems due to several reasons, among which are the effect of mass and/or energy transport and the finite measuring time of the system outputs. These delays are very often neglected. However, they might cause significant deviation from the nominal system trajectory.

We consider the design of optimal control systems in a manner that makes their trajectories insensitive to small time delays. The design strategy is to augment a standard quadratic performance index with a term of sensitivity measure. For deterministic systems the minimization process is carried out using the well-known Minimum Principle. For stochastic systems, the minimization process of the augmented performance index is carried out by transforming the problem into an equivalent static minimization problem. To apply the above methods to our problem of interest, we use the notation of a sensitivity function defined as the first partial derivative of the state vector with respect to the delay, evaluated at the nominal value of the delay, i.e. zero.

Several cases are considered. The delay is assumed to occur either in the plant or in the feedback path. Several system structures are discussed. For each case, both stochastic and deterministic systems are studied. We applied the proposed design strategy to a practical example. The numerical results are analyzed and we conclude that our design scheme is reliable specially if we want to reduce sensitivity of system states according to a desired weighting [C3].

A similar procedure for a general parameter but for discrete-time systems is reported in [A5].

D. Output Feedback Compensator Design

Based on a modified output regulator problem, a design oriented methodology has been developed for the synthesis of output feedback compensators retaining $\ell(1 \leq \ell \leq n)$ optimal eigenvectors from an nth order reference state feedback regulator. Viewing ℓ as a design parameter, Medanic has shown that the case $\ell > r$ leads to a dynamic compensator of dimension $(\ell - r)$ whose parameters can be determined by solution of an associated output feedback pole-placement problem. Using an iterative dyadic pole-placement procedure, an algorithm has been devised recently which determines the solution of this pole-placement problem without a priori assumptions on the compensator dimension. The methodology also can be extended to the class of stabilizable systems and the required compensator shown to possess a separation property. Details of the procedure may be found in [C4], C.S.L. Technical Report R-847 (DC-26). A journal article is being prepared for submission.

E. Zeros of Multivariable Systems

The definition of a zero of a scalar transfer function is well known. Indeed, the properties of zeros are very important for describing the open and closed loop behavior of dynamical systems. There is a natural interest, then, in extending this concept to linear time-invariant multivariable systems. The approach generally taken is to define zeros for multivariable systems so that these zeros retain some property of zeros of a scalar transfer functions. As it turns out, the zeros so defined also have other properties which can be considered generalizations from the scalar case, so the generalization is not unique.

Zeros defined for multivariable systems have been of considerable interest recently. For example, zeros play a major role in the construction of minimal order inverse systems, the construction of reduced order model, decoupling theory, and servomechanism design. They also have been used in relating the structure and coefficients of the quadratic weighting matrices to the resulting eigenstructure of the optimal state regulator and in the stability of the optimal state regulator using high gain feedback.

An in-depth survey of the existing literature on zeros has been made [C1]. The representation of a multivariable system can take three forms: the transfer function matrix, state space system in the time domain, and state space system in the frequency domain. Correspondingly, the definitions of zeros have been extended to each of these representations. In [C1] these definitions are reviewed and their interrelationships are explored. This includes the relationship between different definitions of zeros for the same system representation and the interrelationship of zeros defined for different system representations.

Once zeros are defined, it is of interest to develop algorithms for their efficient calculation. As is turns out, neither the basic definitions nor their elementary properties are well suited to either hand or computer calculation. Therefore, properties were explored which lead to algorithms for computing zeros. Several algorithms for calculating zeros have appeared in the literature. A brief review of the algorithms is included in [C1]. Finally, a new algorithm based on the geometrical properties of linear time-invariant system has been developed. Details are presented in [C1], along with several examples which illustrate the method. A journal article is being prepared for submission.

F. Time-Optimal Control of a Class of Singularly Perturbed Nonlinear Systems

Theoretical studies of nonlinear singularly perturbed optimal controls have been devoted to unconstrained problems. A few results dealing with control constraints are restricted to linear time-invariant systems. In contrast, the most interesting applications have been to nonlinear systems with constrained states and controls. In such complex problems the advantages of order reduction and separation of time scales achieved by singular perturbation methods are manifold, leading to conceptual, computational and control implementational simplifications.

Our recent work has been directed toward the development of an analytical and computational methodology to deal with nonlinear constrained problems. The time-optimal problem is a typical representative of trajectory optimization problems. It is well known that many other cost functional can be transformed into this format.

The time-optimal control of a class of nonlinear singularly perturbed systems possesses the two time-scale property that the optimal control is made of a control in a slow-time scale followed by a control in a fast time-scale. Based on this property a near time-optimal is defined. Two examples illustrating the computation of the near-optimal control and a simple iterative technique have been developed.

G. A Newton-Lyapunov Design for a Class of Nonlinear Regulator Problems

In contrast to the well-developed theory of the linear regulator problem, there are relatively few results on the nonlinear regulator problem. The main difficulty lies in solving the Hamilton-Jacobi equation arising in such problems for the optimal feedback control. In previous work, based on the assumptions that the nonlinearities are weak and the linearized problem is controllable (stabilizable) and observable (detectable), feedback controls are obtained using matched asymptotic expansions. Numerical computation of the series expansions involves tensor equations, and the domain of stability depends on the truncation of the series expansion of the control.

We have extended some results from linear regulators to a class of nonlinear regulators using an iterative scheme. In particular, we obtain analogs of the stabilizing solution to the Riccati equation and the Newton-Lyapunov method for computing the Riccati solution in nonlinear regulators. The iterative scheme differs from earlier ones in that it successively generates improving controls while maintaining a fixed domain of stability. Exponential stability which is crucial in previous work is not essential here.

We consider a class of nonlinear regulators where the system is linear in the control and the cost function to be minimized is a quadratic form of the control. Due to the structure of the problem, the Hamilton-Jacobi (H-J) equation yields a feedback control law with a simple structure. We have shown that the stabilizing solution of the H-J equation is the unique optimal solution. At each stage of the iteration, we improve the feedback control which possesses a domain of stability not smaller than that of the initiating control. The controls are successively solved for from a system of linear partial differential equations, which is an analog of the matrix Lyapunov equation appearing in the iterative solution of the Riccati equation for linear regulators. Furthermore, the improvement in the cost function is quadratic. The uniqueness result guarantees that if convergence occurs, the design method yields the optimal solution.

The numerical solution to the partial differential equations is computed using the method of characteristics which deals with an equivalent system of ordinary differential equations. The result is a feedback control map. In practice, to reduce the amount of data storage and computation, suboptimal schemes such as polynomial approximations, can be used. For further details see [B1].

H. Variable Structure Model Following Control Systems

A new design concept for adaptive model-following control systems capable of shaping the error transient responses is developed using the theory of variable structure systems and sliding mode. It is shown that the resulting model-following control system exhibits adaptive properties inherent in adaptive model-following systems designed by existing methods. An aircraft control problem which has been approached using various model-following techniques is considered and a performance comparison with the present design is made.

The direct application of linear optimal control theory to the design of multivariable control systems ofter encounters two main difficulties in practice. First, it is difficult to specify in terms of a performance index the design objectives. One of the most efficient methods to avoid this difficulty is to use the so-called "Linear model-following control systems" (LMFC). The idea is to use a model, which specifies the design objectives, as a part of the control system. The objective of the controller synthesis is then to minimize the error between the states of the model and the controlled plant. On the other hand, large variations of plant parameters often occur. This second difficulty is also encountered by LMFC. The analysis of the performance of various LMFC systems designs, leads to the development of the so-called "adaptive model-following control systems" (AMFC) which is capable of retaining high performance in the presence of parameter variations.

In general there are two classes of design methods of AMFC systems. Landau, based his method on the hyperstability concept proposed by Popov. Other designs utilize Lyapunov methods. While the primary concern of these design methods is to guarantee that the error between the states of the model and the controlled plant goes to zero, the transient behavior of this error is not prescribed. Only some qualitative discussions are provided on the relationship between the adaptation gains and the speed of the norm of this error.

The adaptive control laws derived using the Lyapunov method for single-input-single-output model reference adaptive systems are discontinuous control laws. These control laws belong to a particular class of discontinuous feedback laws called variable structure control. Feedback systems with variable structure control laws are called variable structure systems (VSS). The salient feature of VSS is that the so-called sliding mode exists on a switching surface. While in sliding mode, the feedback system becomes less sensitive to system parameter variations and disturbance inputs. The connection of VSS and adaptive model reference system is through sliding mode. The advantage of designing AMFC systems by the theory of VSS is that the transient response of the model plant error can be prescribed by the design. We have developed a design procedure for multiinput model-following systems which retains the error transient shaping capability as in the single-input design by utilizing design methods for VSS. We have applied this method to an aircraft control problem.

The plant of this problem represents the three degrees-of-freedom linearized longitudinal state equations of a conventional subsonic aircraft, a Convair C-131B. The model in this case is chosen to be the estimated dynamics of a large supersonic aircraft. This problem has been considered in various model-following papers and it was used in comparing the performance of VSMFC systems to AMFC systems and LMFC systems.

Simulations indicate that a variable structure model-following control law significantly improves the error transient behavior in comparison to that for an adaptive model following control or a linear model-following control. Details are given in [A3].

I. Robust Control System Design

A representation of controllable linear systems has been introduced, which permits assigning poles or characteristic parameters to a state feedback system by a matrix multiplication. This is used as a link between state space and classical parameter plane methods. The system representation maps a point in a $n \times p$ dimensional parameter space $\mathcal{P}$ of characteristic parameters into the $n \times p$ dimensional parameter space $\mathcal{K}$ of state feedback gains, where p is the number of actuators. For $p=1$ the coordinates of the $\mathcal{P}$ space are the coefficients of the closed loop characteristic polynomial, for $p>1$ they are coefficients in a characteristic polynomial matrix and its determinant is the characteristic polynomial. By this computationally simple mapping procedure it becomes feasible to map not only a fixed set of eigenvalues but also regions in the s or z plane, in which the eigenvalues shall be located. This relaxation of the dynamic specifications permits satisfying other typical design specifications like robustness with respect to sensor and actuator failures, large parameter variations, finite wordlength implementation, and actuator constraints. All tradeoffs between such requirements can be made in the $\mathcal{K}$ space. Preliminary results are reported in [B3]. A detailed report will be issued shortly and a journal article is in preparation.

Professor Juergen Ackermann, Visiting Professor with the Decision and Control Laboratory of the University of Illinois, is on leave as Director of the Institute for Dynamics of Flight Systems, DFVLR, in West Germany. We are fortunate to have this opportunity for interaction, and to take advantage of his knowledge of aerospace problems. The entire program has benefited from his presence here.

III. Publications

A. Journal Articles

1. S. H. Javid, "The Time-Optimal Control of a Class of Nonlinear Singularly Perturbed Systems," Int. J. Control, Vol. 27, No. 6, 1978, pp. 831-836.

2. Bruce Krogh and J. B. Cruz, Jr., "Design of Sensitivity Reducing Compensators Using Observers," IEEE Trans. on Automatic Control, Vol. AC-23, No. 6, Dec. 1978, pp. 1058-1062.

3. Kar-Keung D, Young, "Design of Variables Structure Model-Following Control Systems," IEEE Trans. on Automatic Control, Vol. AC-23, No. 6, Dec. 1978, pp. 1079-1085.

4. Bruce Krogh and J. B. Cruz, Jr., "On a Canonical Form in "Design of Senstivity Reducing Compensators Using Observers", IEEE Trans. on Automatic Control, Vol. AC-24, No. 2, p. 353, April 1979.

5. J. B. Cruz, Jr. and M. Sawan, "Low-Senstivity Optimal Feedback Control for Linear Discrete-Time Systems," IEEE Trans. on Automatic Control, Vol. AC-24, No. 1, pp. 119-122, Feb. 1979.

B. Meeting Papers

1. Joe H. Chow, "A Newton-Lyapunov Design for a Class of Nonlinear Regulator Problems," Proc. 16th Annual Allerton Conf. on Communication, Control, and Computing, University of Illinois, Oct. 4-6, 1978, pp. 679-688.

2. S. H. Javid and P. V. Kokotovic, "The Time-Optimal Control of a Class of Nonlinear Systems," 17th IEEE Conf. on Decision and Control, San Diego, Calif., pp. 855-861, Jan. 1979.

3. Juergen E. Ackermann, "A Robust Control System Design," Proc. 1979 Joint Automatic Control Conf., pp. 877-883, Denver, Colorado.

4. C. S. Padilla, J. B. Cruz, Jr. and R. A. Padilla, "Conceptual Framework of SAFER Control," 18th IEEE Conf. on Decision and Control, For Lauderdale, Florida, Dec. 1979.

C. CSL Technical Reports

1. D. K. Lindner, "Zeros of Multivariable Systems: Definitions and Algorithms," Report DC-23 (R-841), May 1979.

2. Y. M. Chan, "Sensitivity Adaptive Control of a Magnetic Suspension System," Report DC-25 (R-843), May 1979.

3. M. E. Sawan, "Design of Optimal Systems with Low Sensitivity to Small Time-Delays," Report DC-27 (R-846), June 1979.

4. W. E. Hopkins, Jr., "Output Feedback Pole-Placement in the Design of Compensators for Suboptimal Linear Quadratic Regulators," Report DC-26 (R-847), June 1979.

IV. Other Activities

Professor Cruz served as President-elect for 1978 and he is serving as President for 1979 of the IEEE Control Systems Society. Other IEEE involvement includes membership on the Education Medal Committee and Technical Activities Board. He is an associate editor of the Journal of the Franklin Institute.

Professor Perkins finished his term as Chairman of the Awards and Fellow Nominations Committee of the IEEE Control Systems Society in 1978. He now serves as Chairman of the Awards Committee of the American Automatic Control Council. He is the Technical Committee Chairman for Economic and Social Systems, Associate Editor for Economic and Social Systems of the Transactions on Automatic Control, and member of the Administrative Committee of the IEEE Control Systems Society.

Professor Kokotovic continues to serve as an elected member of the Administrative Committee of the IEEE Control Systems Society, Associate Editor of Automatica and Chairman of the IFAC Working Group on Singular Perturbations. In 1978 he served as Technical Committee Chairman and Associate Editor for Optimal Systems of the Transactions on Automatic Control of the IEEE Control Systems Society.

Professor Ackermann continues to serve as an Associate Editor for Automatica. He also serves as a member of the International Activities Standing Committee of the IEEE Control Systems Society. In addition to research and teaching of graduate courses in control, Professor Ackermann made a lecture tour of various universities, industrial laboratories, and government facilities.

Profs. Cruz, Perkins and Ackermann visited McDonnell Douglas Corporation in St. Louis to confer with their research staff and to see production facilities for fighter aircraft. Profs. Cruz and Ackermann, together with Major C. L. Nefzger conferred with the staff of the Control Analysis Group of the Air Force Flight Dynamics Laboratory, WPAFB, Ohio.

Dr. Joe H. Chow, now with the General Electric Company, previously with the Decision and Control Laboratory of the University of Illinois and who completed his Ph.D. research at Illinois under AFOSR support, won the 1979 Eckman Award presented at the 1979 Joint Automatic Control Conference.